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Kaewunruen, Sakdirat; Martin, Victor

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Life Cycle Assessment of Railway Ground-Borne Noise and Vibration Mitigation Methods Using Geosynthetics, Metamaterials and Ground Improvement

Sakdirat Kaewunruen [1,*] and Victor Martin [2]

[1] Laboratory for Track Engineering and Operations for Future Uncertainties (TOFU Lab), School of Engineering, The University of Birmingham, Birmingham B15 2TT, UK

[2] Paris School of Urban Engineering, DeEcole des ingénieurs de la ville de Paris, 80 Rue Rebeval, 75019 Paris, France; victor.martin@eivp-paris.fr

* Correspondence: s.kaewunruen@bham.ac.uk

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Abstract: Significant increase in the demand for freight and passenger transports by trains pushes the railway authorities and train companies to increase the speed, the axle load and the number of train carriages/wagons. All of these actions increase ground-borne noise and vibrations that negatively affect people who work, stay, or reside nearby the railway lines. In order to mitigate these phenomena, many techniques have been developed and studied but there is a serious lack of life-cycle information regarding such the methods in order to make a well-informed and sustainable decision. The aim of this study is to evaluate the life-cycle performance of mitigation methods that can enhance sustainability and efficacy in the railway industry. The emphasis of this study is placed on new methods for ground-borne noise and vibration mitigation including metamaterials, geosynthetics, and ground improvement. To benchmark all of these methods, identical baseline assumptions and the life-cycle analysis over 50 years have been adopted where relevant. This study also evaluates and highlights the impact of extreme climate conditions on the life-cycle cost of each method. It is found that the anti-resonator method is the most expensive methods compared with the others whilst the use of geogrids (for subgrade stiffening) is relatively reliable when used in combination with ground improvements. The adverse climate has also played a significant role in all of the methods. However, it was found that sustainable methods, which are less sensitive to extreme climate, are associated with the applications of geosynthetic materials such as geogrids, composites, etc.

Keywords: life-cycle assessment; ground-borne noise and vibration; railway vibration; railway noise; vibration and noise mitigation methods; geosynthetics; metamaterials; ground improvement; Net Present Value

1. Introduction

The railway industry is facing one of its greatest challenges. The increasing demand for railway transport for both freights and passengers leads to an increase in the train speed, the train axle load (carrying burden), and the number of train carriages or wagons (longer train). These needs induce even more noise and vibration, which impacts society, especially in any urban areas where the population is very dense [1,2]. In addition, it is highly likely that more and more people will live in urban areas. These noise and vibration issues will thus have more pronounced impacts on people who work and live along railway corridors, on nearby building acoustics, and also on the comfort of onboard passengers. The environmental and economic cost of railway noise and vibration together with the complaints of residents who lives next to railway corridors have pressured the railway industry to take some meaningful measures to mitigate the effects of railway noise and vibration [3,4]. There are several types of railway noise and vibration problems [5–10]. This study will, however, focus on the ground-borne noise and vibration, generated through track support and foundation.

Ground-borne noise and vibrations from railway tracks are commonly generated by the dynamic loading condition coupling with the train-track interaction. To mitigate these phenomena, many different solutions have been developed and used in practice. When facing a new railway project development, it has thus become somewhat difficult to decide which one is more suitable and financially sustainable. With respect to the environmental issues, it also becomes important to know the impact of each method. To help decision-makers and track designers to improve their choice, many previous studies have been made: [11–15]. However, recent technologies and methods for railway ground-borne noise and mitigation have not been investigated. For example, modern meta-structures have been recently designed computationally but the insight into the life-cycle performance of such methods do not exist.

In this paper, the emphasis will be placed on new methods for ground-borne noise and vibration mitigation which have never been evaluated before according to the open literature review. The study aims to enable new and practical insight in order to help decision-makers such as track engineers, acoustic designers, and rail operators to develop their choice of suitable technique. The methods highlighted in this study include the formation or subgrade stiffening method using geosynthetics, the use of metamaterials, and ground improvements. These methods are relatively new and most of them are either in the modeling and design stage or in the experimental stage. The methods assessed in this study are resonators (meta-structure), inclusions (meta-material), geogrids (subgrade stiffening), composites sleepers, infilled trenches, buried columns (ground improvement), and vibro-compactions (soil improvement). These methods will be evaluated in terms of life-cycle cost to enable a comparison between the new methods and with other previous studies. All of the methods will be presented in detail, including how they mitigate vibration and noise. Then, the life-cycle consideration, assumptions, and methodology will be set identical to allow benchmarking. The outcome of this study will help track engineers and acoustic designers make a better-informed decision on railway ground-borne noise and vibration mitigation methods, improving the economic sustainability of railway networks globally.

2. Mitigation Methods

2.1. Methods Using Metamaterials

2.1.1. Background

Metamaterials are a type of special materials designed and built to have a non-natural property such as a negative index of refraction, for example. Their specific properties are used in different domains of physics. The most interesting aspect that we can apply to railway noise and vibration mitigation is by influencing ground-borne waves in a way that cannot be possible with other traditional materials [16]. Their special properties do not come from the nature of materials of which they are made of, but in the form and disposition of the structure of various different elements in a specific pattern. Metamaterials can affect many kinds of waves depending on the composition design of the meta-structure. Most recent developments are to use the system properties of metamaterials to block waves in a way that cannot be possible with other materials. With this benefit, this approach creates a new application. Metamaterials are used to manipulate electromagnetic radiation, sound waves, or seismic waves [16]. Additionally, they are used to create a new kind of filters, communication cloaking devices, and many other applications.

One of their most important applications is to create a sort of ‘invisibility’ cape. It has been demonstrated that metamaterials in a specific pattern can be used to hide an area from a wave (e.g., seismic waves). Scientists and engineers are developing this application and many experiments have been established. This type of application can be used in civil engineering to protect critical infrastructures and buildings, such as a nuclear power plant, from Earthquake [16,17]. This barrier is placed around the building, preventing damage from a disaster. In light of this new technology, engineers have designed metamaterials and meta-structures, which can be built easily with current civil engineering and construction methods.

The ground-borne vibration generated by train/track interactions is a specific type of seismic waves, and metamaterials can thus be applied to protect buildings (e.g., acoustic theatres, etc.) along the railway corridors. Vice versa, the rail infrastructure can be protected from the natural disaster such as an earthquake. However, building a barrier for each building along the railway corridor can be too expensive so engineers and scientists have to imagine other solutions. These solutions consist of building a variety of barriers of metamaterials in a specific pattern along the railway track. There exist many types of patterns that are being developed and tested but none of them have been implemented in the field. However, a few of these solutions have the potential to be used in applications including the resonator and inclusion methods. All of these methods are re-designed for constructability with minor adaptations of existing construction methods that are already used.

2.1.2. Resonator Method #1

This type of resonator has been developed by Miniaci et al. [18]. The concept of this method is to use metamaterials in a specific pattern to create a barrier in order to attenuate the vibration and reduce it to an acceptable level that cannot damage the surrounding structure and building. Accordingly, this kind of meta-material/structure could be placed between the railway track and the buildings would be protected. It is noted that the pattern of the meta-structures is a matrix of a simple structure in concrete, steel, or with some rubber. In this study, the key focus is to study the hollow cylinder unit cell, which is a cylinder of concrete filled with soil materials. This method is relatively easy to build, and it can be constructed using the same strategies as the diaphragm wall or the bridge stack in civil constructions. The way that this method mitigates the vibration is not fully understood and so there is a lack of data about the performance of this method. However, the initial modeling results stated that it can be used in the railway industry with a proper design, although there is currently no experimental data [18]. At this stage, full insight into the application of this kind of meta-material in the field is limited. However, its existing design can be assessed for a life-cycle cost analysis in order to benchmark the economic sustainability of this method and to evaluate the suitability for its practical use. The application of this method requires a special size of the area that it needs to be built. In fact, the minimum size for the meta-structure matrix is around 10 m $\times$ 10 m. The total area where the resonators should be installed would need around 40 m wide around each side of the railway track. Therefore, this method is not suitable for urban areas where existing buildings are close to the railway track and where every available space is needed to build new equipment, infrastructure or buildings. However, this method would be very suitable for rural areas, greenfield projects, or for places where a railway track runs just near sensitive buildings such as a nuclear plant.

2.1.3. Resonator Method #2

Another different type of meta-material structure has been developed by Krodel et al. [19]. The original idea is the same: mitigate the vibration using a barrier made from metamaterials/structures, but the pattern and the resonator design is different. The design of this method requires a cylinder made from concrete but smaller and not filled with soil. Inside the cylinder, there is a large steel cylinder sandwiched to the concrete using a series of springs. So when there are trains passing by, the vibration product is converted by the resonator into sound internally by the vibration of the sandwiched-steel cylinder. Due to its size, this kind of resonator can be easily built like a buried column or a pile with just a minor adaptation of the equipment. However, the behavior of these resonators is not fully understood and none of them have been built or used in the field. Recently, some scaled experiments have been conducted to complement some computational simulations [19]. The initial results showed that this method can decrease the ground-borne vibrations by more than

10 dB, depending on the direction of the vibration and the frequency. However, due to the experimental state of this method, there exists a lack of historical and time-dependent data. The required size of the meta-structure matrix for this type is smaller than for the previous one (Resonator Method #1). An area of 5 or 6 m wide on both sides of the railway track is necessary, which is more suitable for urban built environments. It was found that this method can be applied in both urban and rural areas. The conversion of the energy into sound waves is the main drawback of this resonator because it causes more internal noise that could be counterproductive and may not be suitable for installation in an urban area with any underground space usage.

2.1.4. Inclusion

The last method using metamaterials highlighted in this paper is the inclusion. This solution was developed by Castanheira-Pinto et al. [20]. The concept is quite different in the way that the inclusion is a series of buried concrete cylinders along and parallel to the railway track. When the position of this cylinder is correctly designed, it will reduce the amplitude of the vibrational wave. The inclusions are buried to a small depth and the size of the cylinder can be the same as a construction pipe. Accordingly, this type of meta-material can be easily set up and does not need much space. However, they need to be buried 10 m from the railway track, and this approach can be suitable for urban and rural areas. The research around this method and the vibration propagation in soil with the inclusion is still ongoing so the mitigation process is not fully understood, similar to the two other methods presented earlier. Despite the lack of experimental or filed data, the design and simulation results are very promising [20]. Therefore, the life-cycle cost analysis to assess the economic feasibility of this method could enable the adoption of this technique for pilot field study or for in-field applications in the future.

2.2. Methods Using Geosynthetics

2.2.1. Background

Geosynthetics are a material made by polymeric compounds. They can be natural or artificial and can be used in many domains such as civil engineering, clothing, or as materials to build different kinds of objects. Most geosynthetics are made from fibers that are knotted or glued to form a new fabric. In civil engineering, their properties can be used to reinforce soil, sustain embankment, filter or partition two different soils, for example. These kinds of materials have gained momentum for various applications around the world.

In the railway industry, geosynthetics are also widely used [21]. Some of these methods have been already assessed in terms of life-cycle cost analyses [11], but this is not the case for all of them. The process to mitigate noise and vibration using geosynthetics depends on the methodologies and materials so that case-by-case evaluations should be carried out.

The methods highlighted in this study are geogrids (to stiffen the formation or subgrade), composite sleepers, and Geofoam-infilled trenches. Contrary to metamaterials, these methods have been used for many years and are well known [22] so the data of field behaviors and the process of vibration mitigation can be found in the open literature. It is noted that the implementation processes for all of these methods are also well known and many railway companies have an extensive experience of using them.

2.2.2. Geogrid

Geogrids are one of the most common methods using geosynthetics in the railway industry. This method consists of a geogrid placed under the ballast layer or between two of them. When the geogrid is added, it reinforces the ballast layer and reduces the vertical settlement [22,23]. The vertical settlement is one of the main causes of the rail track geometry deterioration (i.e., increased roughness) that creates additional noise and vibration, as well as increasing maintenance costs. Therefore, geogrids have been used to reduce track deformation and prolong the track geometry. The installation of geogrids also reduces the maintenance frequency because they can stiffen the layer of track support formation. Grids/ballast interaction and geogrids properties are well known since there have been a large number of studies about it. These studies showed that the reduction of noise and vibration is dependent on the ballast and the subgrade properties. Over the past years, geogrids have been used mainly in combination with other methods and particularly with ground improvement methods. In this study, the combination of the geogrid application with other ground improvement methods will be investigated. The installation of geogrids is relatively convenient and the manufacturers sell geogrids in a roller so that the geogrids can be unrolled over the formation before installing ballast. This technique is very suitable for all new and existing railway tracks because it can be added during ballast renewal or track reconstruction. This is the reason that this method is widely used in the railway industry and also at a relatively low cost.

2.2.3. Composite Sleepers

Another emerging method that can be associated with geosynthetics methods is polymer composite sleepers [24]. This method adopts the use of a new type of sleeper made from composite materials and replaces either aging timber or concrete sleepers. Composite sleepers are widely used in Japan and to a certain extent, in Australia, but not many are used in Europe because of their higher cost compared to concrete sleepers. However, with the increase of vibration and noise mitigation needed, they have begun to gain momentum in the railway industry. Composite sleepers tend to reduce noise and vibration better compared to brittle concrete sleepers, and the composites can absorb much more strain energy than concrete. They have also been used to reduce any impact noise and vibration at switches and crossings. Their installation is also easy because they can be installed in the same manner as every other sleeper. They can also be used for all types of railway tracks, in both rural and urban areas, and also for new and old tracks. The most important drawback of this kind of sleeper is the unit cost compared to timber, steel, or concrete sleepers; but, with their recent development, it is supposed that their cost will decrease in the coming years. Composite sleepers can also reduce the need for maintenance and the maintenance costs over the whole life cycle.

2.2.4. Geofoam Infilled Trench

To attenuate ground-borne vibrations generated by the train-track interactions, there is a recent method by using trenches along the railway lines. Trenches have the same role as the vibration and noise barrier has in terms of wave reduction. Their mitigation principle is the same. Trenches create an obstacle for the wave and create a 'shadow' behind them where the vibration is being suppressed. Many studies have been conducted to understand soil behaviors with various types of trenches and to know which type of trench is the best one [11,25,26]. Most data suggested that emptied trenches with nothing inside are the best ones to suppress ground-borne vibration, but this type of trench is difficult to keep maintained and secured because it needs to be supported and stabilized by especially improving the surrounding soil or by foundation structures. To resolve this problem, many types of infilled trenches have been developed. One of them adopts geosynthetic materials and there are trenches infilled with Geofoam [25,26]. These infill blocks are made from composite materials, which are widely used to reinforce bridge abutment and embankment. The construction of this infilled trench is the same as other types with a Geofoam block installed inside. Similar to noise barriers, a trench needs to be built at a distance of a few meters from the track. Since it can be built after the track construction, a trench could be built in urban and rural areas and also for new and existing tracks. In this study, it is considered that this method is reliable and practicable.

2.2.5. Concrete Infilled Trench

To compare Geofoam infilled trenches with other types of trenches, a concrete infilled trench has been considered [11]. This type of trench was designed to solve the same problem as Geofoam infilled trenches. A concrete infilled trench is a basic trench filled with concrete (and sometimes bentonite) inside. This kind of trench is much more common than the Geofoam one because concrete or bentonite is relatively easier and cheaper to find and use. In addition, concrete is more common and inexpensive. The mechanism that concrete trenches reduce vibration is similar to the other type of trench. However, some studies showed than concrete-filled trenches are less efficient than Geofoam trenches due to concretes' mechanical and dynamic properties [8,27,28]. Considering the potential adoption of concrete-filled trenches, there is a need to assess the life-cycle performance and compare these two types of infilled trenches. In this paper, the point of view of life-cycle cost and systems thinking approach have been highlighted to identify the suitability, reliability, and life-cycle sustainability of the methods.

2.3. Ground Improvement Methods

2.3.1. Background

The ground-borne vibrations generated by train-track interactions depend largely on the variable subgrade properties. Stiffening the subgrade could suppress the vibrations from the track. The engineering properties of the ground where the track is built can be different and varied; and can depend on the environmental conditions and many other factors. In many circumstances, the soil could be weakened and unable to support the track components or to appropriately dampen vibrations [29]. To suppress ground-borne vibrations and to improve soil properties, various ground improvement methods are established in the railway industry.

Ground improvement methods are widely used in civil engineering for many reasons. They are used mainly to strengthen the foundation to support the building or infrastructures or to avoid ground liquefaction in case of earthquakes. They are also used in the railway industry for similar reasons. However, ground improvement methods can also be used as vibration mitigation methods [29]. In this paper, three techniques using ground improvement methods to mitigate ground-borne vibrations will be considered. These methods are the vibro-compaction of formation (also called vibro-flotation), ballasted columns, and buried concrete columns. All of these methods are already used in civil engineering projects and have been used in railway tracks. In many cases, a geogrid is also added to improve the interface between the ballast and formation. It can also be inserted to strengthen or stiffen the layer of track support formation. The life-cycle costs of the combination between geogrids and all of the methods are then assessed in this study.

2.3.2. Vibro-Compaction

The vibro-compaction or vibro-flotation method increases the compactness of the soil to increase the soil stiffness and decrease the risk of settlement [30]. The process commences by penetrating the vibrating device in the soil, and the vibration will compact the soil by rearranging the granular structure. Due to the penetration process, this method cannot be applied to all types of soil. It can only be used in silt, sand, and clay. This is also a well-known method and the process has been adopted in various industries [30].

This method can be implemented underneath the railway tracks so it does not need extra space than the track requires. Although the method has been implemented for the construction of new railway tracks, the method for existing tracks is not available and being developed. The method needs a few quantities of materials to replace the loss of volume due to compaction.

2.3.3. Ballasted Column

Another ground improvement method that can be used to improve the soil stiffness and reduce vibrations is ballasted column [31]. This method is quite similar to vibro-compaction. A vibrating device is used to compact the soil and add gravel inside the soil to form a buried column. This kind of column (in the horizontal direction) has the advantage of creating an area with a good permeability and drains water away from the track. This method also needs a soil type that can be compacted so it can be only used in stabilized sand, silt, and clay.

Ballasted columns can also only be constructed in a new railway track because they are implemented under the ballast. Because of this, it cannot be used in most urban areas where tracks are already built with constrained clearance. This method also uses gravel as its material to replace the soil, requiring additional compaction. This technique enables a better soil stiffness.

2.3.4. Buried Concrete Column

This ground improvement method is different from the two others. It is more complex in terms of the construction approach. There are many ways to build this concrete column. The most common one is to use a drilling machine to create holes and when it is at the right depth, the drill is then used to pour the concrete inside the holes to form a concrete column embedded within the compacted soil. Contrary to the other methods, this method can be used in soils composed of gravel and sand [31].

Similar to the ballasted column and vibro-compaction methods, this method can be used on new railway tracks. However, due to the physical constraints, the application of this method for existing railway tracks is limited. This method also uses concrete that causes a high environmental cost compared to the other methods [32,33]. The illustrations and indicative performance of each method are in Appendix A.

3. Assumptions and Computation Methods

3.1. General Assumptions

To benchmark the economic sustainability of all the methods, the common bases, assumptions, and the methodology to obtain their life-cycle cost analysis are set to be identical. In this study, the impact of the extreme climate on each method is highlighted. The aim is to develop new insights into the sustainability of the methods under normal conditions (control case) and when they are exposed to adverse climate conditions. The railway track chosen in this study is a 100 m double track (two tracks in parallel). The double track represents the track structure of most of the railway lines in Europe, which is the reason why it was chosen for this study [34]. A length of 100 m is chosen for the unit computation. This double track is also 10.5 m wide according to classical clearance designs and interoperability recommendations. The ballasted track is highlighted in this study since it is of the same types used by the majority of railway tracks worldwide. This type of railway track tends to cause more troublesome issues with ground-borne vibrations [4,5]. In addition, all the aforementioned methods including geogrids can be applied to ballasted tracks. When evaluating the maintenance tasks without any mitigation methods, standard recommendations for track resurfacing (or track alignment restoration) have been used [34]. These tasks include tamping, stone blowing, and track inspection. According to the prices shown in the study, the costs are generalized for 100 m of double track: 3400 € for tamping, 2800 € for stone blowing and 170 € of track inspection [34,35]. The total cost for each maintenance operation for the track is 6370 € for 100 m of double track [35]. All of these general assumptions are used for all of the relevant cases and all of the identical tracks. Specifically, as follows:

3.1.1. Control Case

The control case is the case with normal conditions and without any adversity or extreme conditions. For the control case, the normal average temperature is around 20 °C and there is no extreme rainfall and particular events such as storms or flooding in this case. The only factors that affect the track components are the natural fatigue life of the materials and the number of cycles of loading due to the train. Thus, in this case, and according to the above recommendation, the maintenance frequency is yearly. The maintenance cost is estimated at 6370 € per year [35]. These assumptions are used for all of the relevant methods unless it is specified in the details of the calculation.

3.1.2. Adverse Climate Case

To measure the impact of the weather and the climate on all of the methods, the adverse climate effects found in Europe or North America are considered. The adverse climate is considered when the railway tracks are exposed to extreme hot and cold temperatures, which can affect the behavior of the track and its components. In addition, railway tracks commonly face heavy rain, storms, and floods. The return period of extreme floods is chosen to be at 10 years according to the British government's recommendation [36–38]. Floods can significantly affect the behavior of the track, resulting in an increase in the maintenance cost and inspection for all of the relevant methods.

All of the addressed assumptions will be adopted in this study for all the methods to enable a common-ground comparison using the same baseline.

3.2. The Net Present Value

To benchmark all of the mitigation methods based on their life-cycle costs, a methodology to evaluate this cost should be generalized. In practice, the cost of an investment must be represented by the Net Present Value (*NPV*). This NPV method is generalized in order to take into account all of the costs and profits (detailed cash flows) of an investment during a period of time and to also take into account the time effect on the value of the money. The formula to calculate the *NPV* is the following:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{1}$$

where:

N is the time period chosen to do the *NPV*

i is the discount amount

t is the iteration of time

R_t is the net cash flow of the year t. R_0 is the initial cost or the construction cost.

In this study, the period of time used to calculate the *NPV* is 50 years. This period of time corresponds to the lifespan of the ballasted track and most of the infrastructure assets in harsh environments. This is also the common period of time taken by most of the previous studies on the life cycle of rail infrastructures and fixed assets [34,39].

The discount rate or expected rate of return on an investment is the expected amount that the investment will gain or profit each year. According to this study, its values have an impact on the final conclusion of the study and can also influence the final choice. In this paper, a discount amount of 5% was chosen. This corresponds to the amount advised by the government and the amount generally used for this type of study and government projects [34]. The period of time and the discount rate are identical for all of the cases and methods. The calculation of net cash flow for each case is different because the cash flow items (cost/benefit) are varied for each method.

3.3. Assumptions and Quantity

Before calculating the NPV for each method, the initial cost and the maintenance costs for each mitigation method are estimated. The labor cost is not considered in this study as it is a highly variable cost. The unit cost takes into account the material cost and the installation cost. For this study, the concrete cost is 90 € per cubic meter according to the market price [35].

3.3.1. Resonator 1

This type of resonator is designed in accordance with the guideline in Reference [18]. The resonator is an empty cylinder and is made from concrete. To know the unit material cost we just need the volume and the concrete cost. The inner radius is 3 m and the outer radius is 4 m. The length of the cylinder is also 20 m. A bridge stack foundation or diaphragm wall is considered for this type of design. The market price for a diaphragm wall is around 23 € per square meter. The matrix for each side of the track is formed with 4 rows of resonators. The width of the square of the matrix that contains the resonator is 10 m; so for 100 m of track, there are 10 resonators by row.

In the control case, the concrete buried in the soil does not need any maintenance. Based on the distance of the structure to the track, it can be supposed that there is no impact of the meta-structure on track maintenance. In the adverse climate case, there are no impacts of weathering on the resonator because it is a buried concrete structure so the extreme temperature and floods do not have any significant impact. It is implied that the maintenance cost is relatively the same for both cases. All of the costs are summarised in Table 1.

3.3.2. Resonator 2

The same methodology is applied to calculate the unit cost for this type of resonator. The design of this method is based on the following study [19]. The dimensions of the resonator are 2 m in length, an inner radius of 0.57 m, and an outer radius of 0.60 m. The steel piece inside is a 2000 kg piece. With these values, the unit material cost is 1300 €. By comparing the installation cost with similar structures (i.e., prefabricated concrete piles), the installation cost for this kind of pile can be estimated to be 6800 € per unit.

The matrix for this resonator is made by 5 rows of resonators with the distance between 2 resonators being 0.9 m according to the study [19] (or about 1.5 m between the 2 resonator centers). Based on the design and its position (buried in the soil) on the railway corridor, it can be found that the installation costs are similar for both the control and adverse climate cases, as shown in Table 1.

3.3.3. Inclusion

Inclusions are also built from concrete cylinders with the diameter of 0.6 m. The material cost can be calculated using Reference [35]. Considering the shape and the depth where the inclusion is buried, it can be assumed that the inclusion can adopt similar construction activities as those of every water pipe. Therefore, the installation cost can be estimated in relation to the water pipe installation cost. According to a previous study [20], the most cost/performance effective design is to install 3 inclusions on each side of the track.

Inclusions are a set of totally buried concrete cylinders so when they are installed, they do not need any maintenance in the control case. Due to its position and location, the maintenance of the track will not be affected. In the adverse climate case, extreme temperatures do not have an impact on the meta-structure because the temperature in the soil is insensitive. Similarly, the flood condition plays a very little effect on the inclusion condition.

3.3.4. Geogrids

Geogrids are commonly installed under the ballast so their surface interlocks with the ballast surface. In this case, for 100 m of track, the ballast-geogrid contact surface is also 1050 m^2. Geogrids are generally sold in rolls and each roll costs 885 € according to the manufacturer's price and each roll is for 150 m^2. The installation of geogrids is really easy. The geogrid can be unrolled under the ballast by a trackwork machine. For this reason, the additional installation cost is relatively negligible.

According to previous studies [22,23], geogrids decrease the maintenance frequency by reducing the effect of vibrations on the ballast. The routine maintenance frequency for ballasted tracks with geogrids is around 3 years in the control case and about 2 years in the adverse climate case (due to the effect of flooding that can undermine the formation). In the adverse climate case, the influence of floods can be significant. Indeed, after each major flood, the geogrid needs to be replaced by a new one because the flood damages the geogrid and clogs the interlocking surface with soil. With a return period of 10 years for floods, the lifespan of the geogrids is reduced to 10 years in the adverse climate case.

3.3.5. Composite Sleeper

Composite sleepers can replace other types of sleepers in certain locations (e.g., switches and crossings, bridge ends, etc.). According to the manufacturer's price, each composite sleeper costs more than 250 € (depends on the manufacturer). In this study, there is a sleeper every 0.60 m on average since this is the common spacing value recommended by the government and professionals of railway engineering. Because the composite sleepers can simply replace other sleepers, there no additional cost of installation compared with other the methods. It is thus considered that the installation cost is 0 (nil).

According to a previous study [15], composite sleepers can reduce the maintenance frequency. For both cases (control and adverse climate cases), the maintenance frequency can be reduced by half. It is noted that adverse climates have no impact on the composite sleepers.

3.3.6. Concrete Infilled Trench

According to previous studies [11,25,26], the concrete infilled trenches have a depth of 6 m and a width of 1 m. They are also made with classic concrete so the material cost can be simply quantified. Trenches are installed on each side of the track. Then, it is supposed that this kind of trench can be built like a diaphragm wall, so the installation cost can be obtained according to the market price for the construction of this type of structure. The concrete infilled trenches are totally buried concrete so they do not need any significant maintenance. Additionally, because of their position and location, they do not affect the track maintenance process. Thus, the cost of track maintenance will not change.

For both adverse climate and control cases, the maintenance frequency does not change. Because the structure is buried, the extreme temperature ranges have a very little impact on this structure and floods also have an insignificant impact on the concrete infilled trenches.

3.3.7. Geofoam Infilled Trench

Geofoam infilled trenches also have a depth of 6 m but the width is 0.75 m because it corresponds to the width of a pre-manufactured Geofoam bloc. Indeed, Geofoams are mainly sold in a block of 2 m by 0.75 m by 0.75 m. According to the manufacturer data, each block costs around 107 €. Similar to the concrete infilled trench, there is a trench on each side of the track and due to its position, the trenches do not impact the track maintenance process as well as the maintenance cost. However, for the trenches itself, there is no extra maintenance need because the Geofoam trench is totally buried.

In the control case, there is no particular issue with the use of Geofoam infilled trenches, but in adverse climates, the rain and floods can affect Geofoam blocs. In fact, Geofoam blocs are sensitive to water and the pressure created by floods. Therefore, after every flood, the geofoam needs to be replaced by a new one. With a return period of 10 years, the lifespan of Geofoam infilled trench is estimated to be 10 years. However, the maintenance frequency is relatively the same for both cases.

3.3.8. Concrete Buried Column

Concrete buried columns are designed using the ground improvement method standard. They are 10 m in depth and their diameter is 0.6 m. The concrete use for this kind of structure is the classical one. Therefore, it is relatively easy to calculate the material cost. For the installation cost, the price proposed by construction companies who build this type of structure has been adopted. The ground improvement standard [35] is also used to calculate the number of columns needed in this case. These structures do not need any maintenance and because they suppress the propagation of vibrations underneath the track. It is supposed that the maintenance process of the track is not affected. Ground improvement methods are also constructed to avoid soil liquefaction. As such, the flood conditions have a negligible impact on all of the ground improvement methods. Additionally, because they are buried, extreme temperatures are not influential.

3.3.9. Ballasted Column

As for buried concrete columns, European technical standards to design the column are adopted [35]. The given recommendations to calculate the number of columns are that each column is 18 m depth and the diameter is 1 m. To calculate the materials cost, the price of ballast is 27 € per tons. For the maintenance cost and the maintenance frequency for the different cases, the assumptions are the same as for the buried concrete columns.

3.3.10. Vibro-Compaction

Vibro-compaction is the only method that does not use any additional materials so the extra material cost is obviously null. The depth of vibro-compaction is 15 m and the area of treatment is the total area of the track, about 1050 m^2. Construction companies with expertise in ground improvement have provided the cost per m^3 for this study. This cost is around 8.5 € per m^3 with 3000 € being the fixed cost. For all of the maintenance costs and frequencies, the assumptions are the same as the two other ground improvement methods.

When geogrids are combined with ground improvement methods, the assumptions of the two methods are taken into account for all of the costs. However, when only the geogrid needs to be changed, merely the costs for the geogrid are taken into account. All the costs and information about all the methods are summarized in the following tables.

Table 1. General data of the mitigation methods.

(A)

Method	Materials Cost	Installation Cost (€)	Quantity	Initial Cost for 100 m of Track
Resonator 1	80,000 € per unit	101,004 per unit	80	7,208,000
Resonator 2	1300 € per unit	6800 per unit	670	4,427,000
Inclusion	50 €/m	25,000	600 m	55,000
Geogrid	6 €/m^2	0	1050 m^2	6300
Composite sleeper	250 € per unit	0	335	83,750
Concrete infilled trench	540 €/m	5250	200 m	113,250
Geofoam infilled trench	430 €/m	5250	200 m	91,250
Concrete buried column	509 € per unit	320,080	736	694,704
Ballasted column	1209 € per unit	107,000	290	457,610
Vibro-compaction	No materials	8.5 per m^3 + 3000	15,750 m^3	136,875

(B)

Method	Control Case		
	Maintenance Cost (€)	Maintenance Frequency (Years)	Lifespan (Years)
Resonator 1	6370	1	More than 50
Resonator 2	6370	1	50
Inclusion	6370	1	75
Geogrid	6370	3	20
Composite sleeper	8375	2	50
Concrete infilled trench	6370	1	50
Geofoam infilled trench	6370	1	50
Concrete buried column	6370	1	More than 50
Ballasted column	6370	1	More than 50
Vibro-compaction	6370	1	More than 50

(C)

Method	Adverse Climate Case			Particularity
	Maintenance Cost (€)	Maintenance Frequency (Years)	Lifespan (Years)	
Resonator 1	6370	0.5	More than 50	Experimental method
Resonator 2	6370	0.5	50	Experimental method
Inclusion	6370	0.5	75	Experimental method
Geogrid	6370	2	10	-
Composite sleeper	8375	1	50	Replace classic sleeper
Concrete infilled trench	6370	0.5	50	-
Geofoam infilled trench	6370	0.5	10	-
Concrete buried column	6370	0.5	More than 50	Can only be used for sand and gravel
Ballasted column	6370	0.5	More than 50	Can only be used for sand, silt, and clay
Vibro-compaction	6370	0.5	More than 50	Can only be used for sand, silt, and clay

4. Results

4.1. The Outcome of the Analysis

The calculation of the NPV, which is widely accepted as the most suitable method to consider detailed cash flows and to evaluate the value of the investment, allows us to generalize the economic effects and to enable a fair comparison and benchmarking of all of the methods in the same baseline. The following figures show the NPVs of all the methods in the control case (Figure 1) and in the adverse climate case (Figure 2).

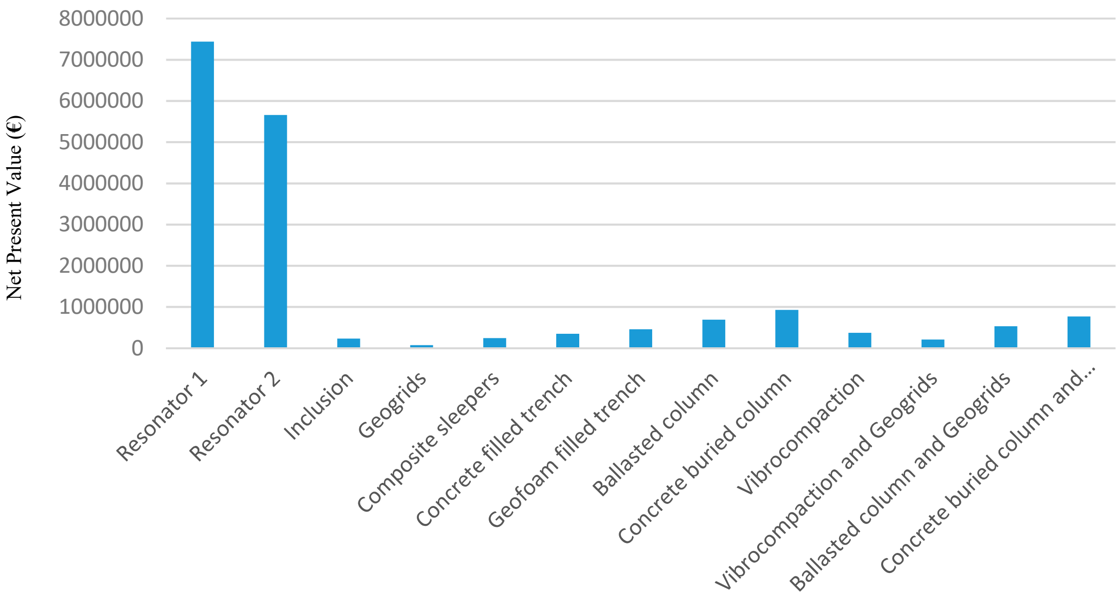

Figure 1. The Net Present Values (€) in the control case.

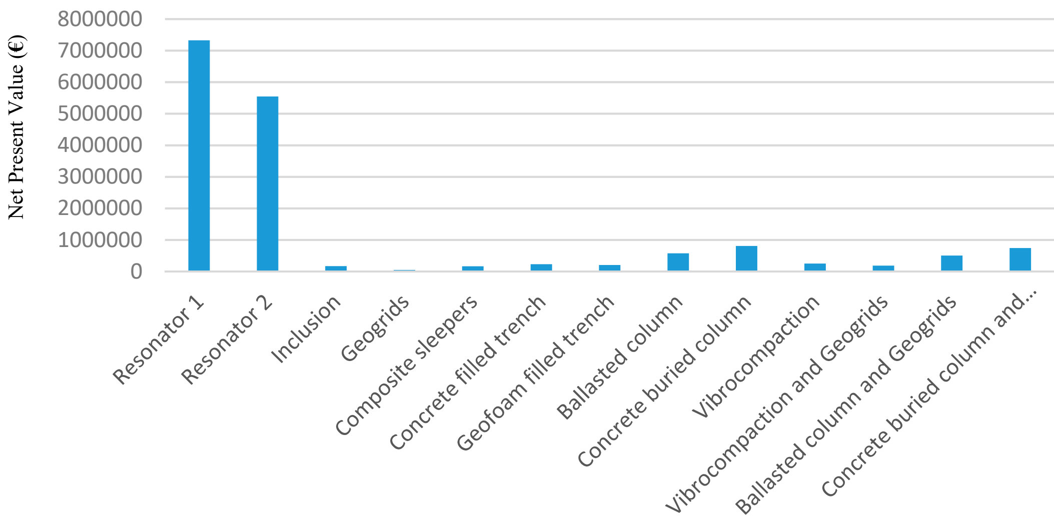

Figure 2. The Net Present Values (€) in the adverse climate case.

It is very clear from Figures 1 and 2 that the resonators have very high costs compared with the costs of other methods considering both cases (normal and adverse conditions). This significant cost is not viable for the railway industry to adopt them for a railway vibration and noise mitigation method. This cost is considered to be too expensive per unit and a large number of units will be required along the railway track. The use of resonators in the railway industry is not proven presently but if some progress and developments are made in the future, they may become usable. Figures 3 and 4 highlight the comparison among the common mitigation methods (without both resonators).

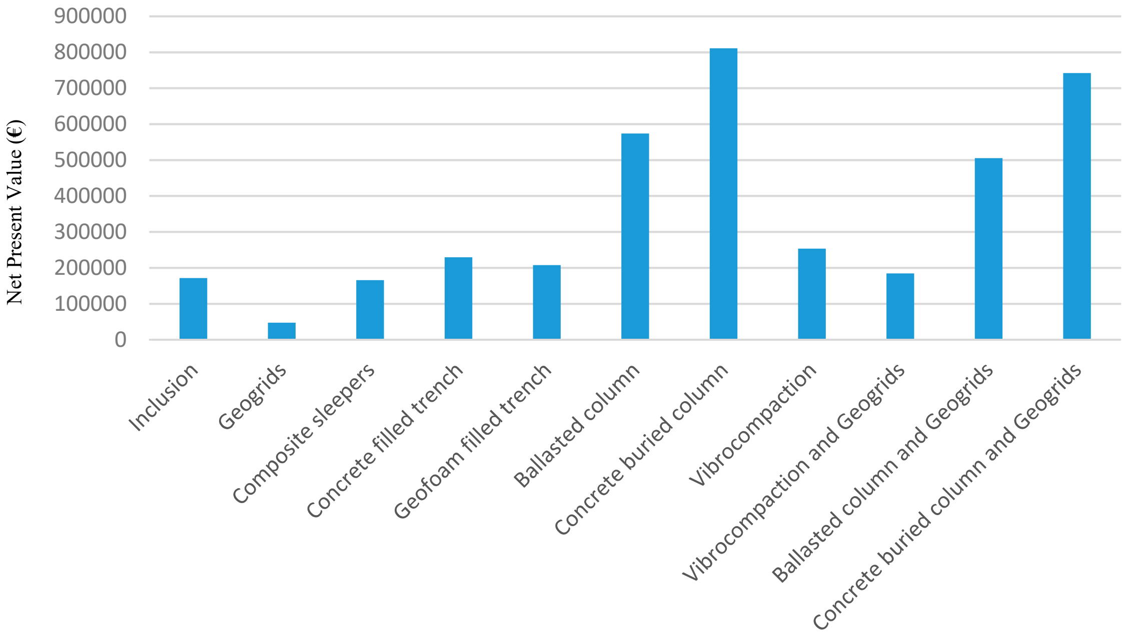

Figure 3. The Net Present Values (€) in the adverse control case without the resonators.

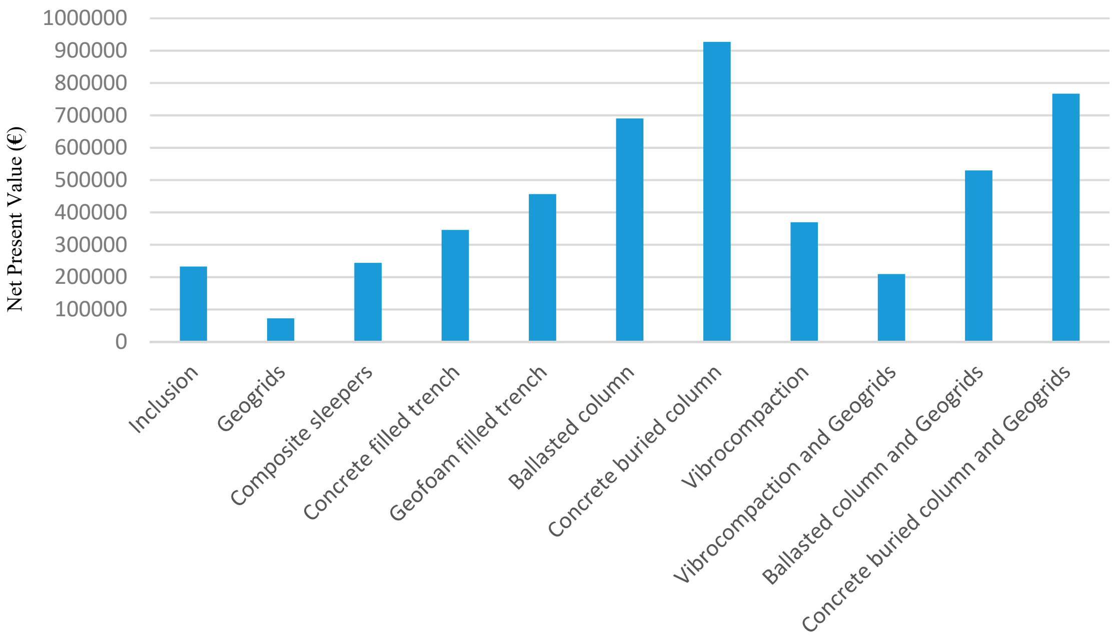

Figure 4. The Net Present Values (€) in the adverse climate case without the resonators.

Considering Figures 3 and 4, it is apparent that geogrids are the most cost-effective method for both cases (adverse climate and control cases). However, the relatively poor performance of the geogrid compared with the other methods in terms of vibration mitigation do not make them the best choice if they are used alone. Indeed, the findings reveal that the use of geogrids with another method reduces the maintenance cost and the total life-cycle cost. By using geogrids, ground improvement methods become cheaper and can be a very good choice if there is a need of ground improvement for other reasons (i.e., to avoid soil liquefaction, to strengthen soft soil, to enhance critical track velocity). It is noted also that the inclusions can be suitable for vibration mitigation since their cost is not prohibitive compared with other common methods such as trenches or composite sleepers.

4.2. Adverse Climate

In many regions around the world, railway tracks are facing adverse climates with high and low temperatures as well as floods. This kind of incidental event also incurs in Europe, so it is necessary to highlight the impact of an adverse climate on the life-cycle costs of every mitigation method adopted in railway tracks. This will enable a new insight into their adaptation in the future. Figures 5 and 6 show the comparison between the life-cycle costs in the control case and the costs in the extreme climate case.

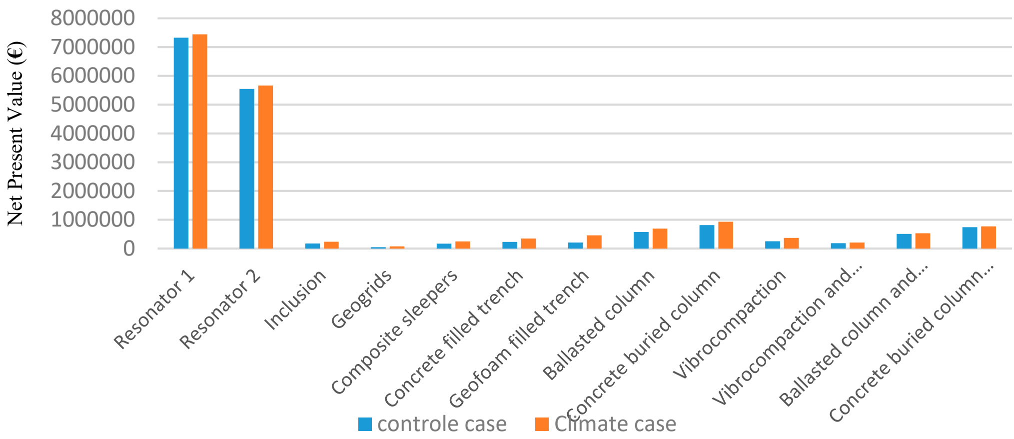

Figure 5. The comparison of the Net Present Value (€) between the control case and the adverse climate case.

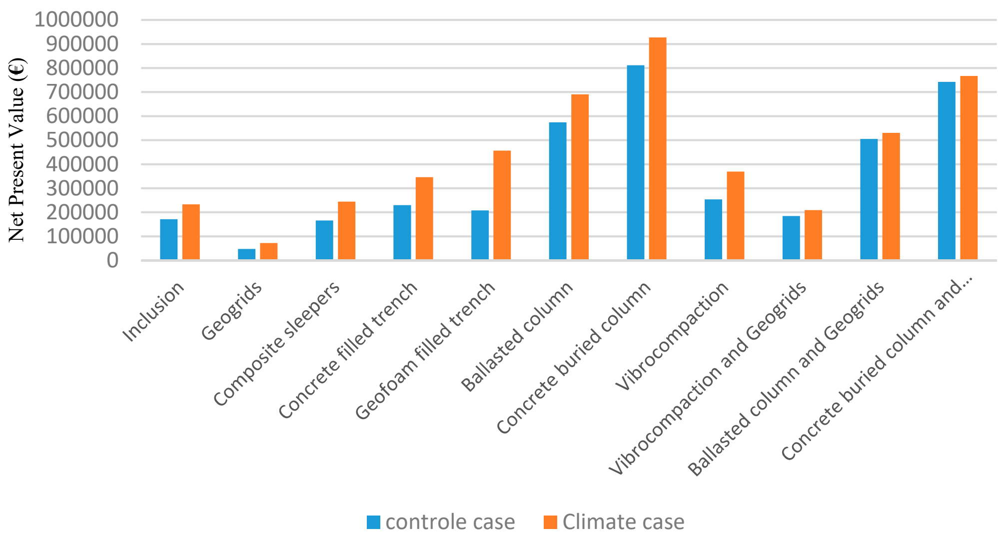

Figure 6. The comparison of the Net Present Value (€) between the control case and adverse climate case, without resonators.

Based on the analyses, the life-cycle costs in the adverse climate case are generally higher for all of the methods than under normal weather conditions. This is due to the increase of the maintenance frequency derived from the weakened stability and stiffness due to the extreme weather. However, it can be observed that the extreme climate conditions have a different impact on some of the methods and it is clear that some of them are more sensitive than others. To highlight this sensitivity, the percentage of rise (incremental cost) has been tabulated in Table 2.

Table 2. The rise of life-cycle cost between the control case and the adverse climate case.

Method	Rise in %	Method	Rise in %	Method	Rise in %
Resonator 1	1.59	Concrete infilled trench	50.66	Vibro-compaction and Geogrid	13.42
Resonator 2	2.10	Geofoam infilled trench	119.85	Ballasted column and Geogrid	4.90
Inclusion	35.78	Ballasted column	20.26	Concrete buried column and Geogrid	3.33
Geogrids	52.14	Concrete buried column	14.34	-	-
Composite sleeper	47.28	Vibro-compaction	45.93	-	-

It is apparent from Table 2 that the Geofoam infilled trench is the most sensitive method, and in the case of floods, its cost will be double and the method becomes the most expensive option compared with concrete infilled trenches. It is also noted that the relatively inexpensive methods tend to be more sensitive to and endure a larger impact from the extreme climate conditions. As a result, engineers should be prudent and careful when designing and selecting the best option or method for railway noise and vibration mitigation. Based on this study, it is clear that the impact of the extreme weather and the climate (especially with global warming, which could cause more natural disasters such as flood) can significantly affect the performance of railway tracks and there is a necessity to identify the cost implication due to climate adversity on the track maintenance prior to the installation of any railway noise and vibration mitigation method.

4.3. Parametric Effects

To reflect the effect of economic agglomeration, the effects of the discount rate and construction and maintenance costs on the overall life-cycle costs (normal weather case) have been demonstrated in Tables 3 and 4. The results clearly show that the rise of life-cycle costs between the control and adverse weather cases is sensitive to the discount rate. It is noted that if the discount rate or expected rate of return is higher, the difference in life-cycle costs between the normal and adverse cases becomes noticeably lesser. These trends can be observed for every method of ground-borne noise and vibration mitigation.

By considering the effect of construction and maintenance costs as tabulated in Table 4, it is clear that the reduction in the construction and maintenance costs will increase the rise in the cost between the control and adverse weather conditions. However, the increase in the construction and maintenance costs (e.g., from the variation of labor cost) will suppress the rise in the cost between the control and adverse cases. Despite the similarity of trends, it is noted that the Geofoam-filled trenches are an exception. It is found that the increase in the construction and maintenance costs for Geofoam-filled trenches will also increase the rise of the life-cycle cost between control and adverse climate cases. This is because the capital costs for Geofoam-filled trenches are relatively higher than the annual maintenance costs. When the trenches experience extreme climates, the cost for the total renewal of the structure becomes significant, resulting in the rise of the life-cycle cost. This insight implies that this Geo-foam filled trench solution might not be suitable for regions or countries where the economic agglomeration effect is vulnerable (for example, in countries where labor costs fluctuate significantly over short periods of time). Note that the uncertainties from local cost variations, contingency plans, currency exchanges, and so on can be justified by individual risk management frameworks of constructors project developers associated with international monetary institutions (e.g., World Bank, Asian Development Bank, etc.).

Table 3. The effects of the discount rate on the rise of the life-cycle cost between the control and adverse climate cases.

Method	% Rise in the Life-Cycle Cost Increment between the Control and Adverse Climate Cases			
	Discount Rate = 2.5%	Discount Rate = 5% (Baseline)	Discount Rate = 7.5%	Discount Rate = 10%
Resonator 1	2.45	1.59	1.13	0.87
Resonator 2	3.22	2.10	1.50	1.15
Inclusion	53.32	35.78	20.09	6.90
Geogrids	53.18	52.14	51.23	50.14
Composite sleeper	53.34	47.28	40.68	35.08
Concrete infilled trench	61.47	50.66	42.19	35.80
Geofoam infilled trench	151.40	119.85	95.65	77.67
Ballasted column	28.31	20.26	15.30	12.13
Concrete buried column	14.34	14.34	10.63	8.33
Vibro-compaction	56.90	45.93	37.65	31.57
Vibro-compaction and Geogrid	18.46	13.42	10.27	8.22
Ballasted column and Geogrid	7.30	4.90	3.57	2.78
Concrete buried column and Geogrid	5.04	3.33	2.41	1.86

Table 4. The effects of construction and maintenance costs on the rise of life-cycle costs between the control and adverse climate cases.

Method	% Rise in the Life-Cycle Cost Increment between Control and Adverse Climate Cases		
	Reduction in Construction and Maintenance Costs 25%	Increase in Costs 0% (Baseline)	Increase in Construction and Maintenance Costs 25%
Resonator 1	2.11	1.59	1.27
Resonator 2	2.78	2.10	1.69
Inclusion	42.00	35.78	30.09
Geogrids	51.65	52.14	52.58
Composite sleeper	47.28	47.28	47.28
Concrete infilled trench	57.42	50.66	45.33
Geofoam infilled trench	116.92	119.85	122.22
Ballasted column	23.92	20.26	17.58
Concrete buried column	16.21	14.34	12.85
Vibro-compaction	52.93	45.93	40.57
Vibro-compaction and Geogrid	16.57	13.42	11.28
Ballasted column and Geogrid	5.95	4.90	4.16
Concrete buried column and Geogrid	3.82	3.33	2.95

5. Conclusions

With the increasing demand for freight and passenger transport, the speed of trains, the number of train wagons/carriages, and the axle loads are expected to increase significantly. These can induce an increase in railway noise and vibration problems along the railway network, especially in an urban area where the railway tracks are closer to buildings and infrastructures. As a result, the railway industry faces a big challenge to improve the transport networks while maintaining or reducing the noise and vibration level. There have been a large number of noise and vibration mitigation methods in the railway industry since the 1950s. The progress of the development has recently been improved due to the advancement in construction and manufacturing technologies. Many new technologies have been established such as meta-material, geosynthetics, and so on. However, a life-cycle cost evaluation underpinning economic sustainability still does not exist.

To help decision-makers and engineers design and select the most suitable method for their networks, many studies have been carried out to understand their technical performance and how they mitigate railway vibration and noise. However, very few studies have identified the life-cycle cost and the longer-term performance over the whole life of the infrastructure. This has motivated us to highlight the life-cycle evaluation in uncertain settings. The emphasis of this study is placed on the ground-borne noise and vibration mitigation techniques. The methods focused in this study are meta-structures using resonators and inclusions, geogrids, composite sleepers, Geofoam infilled trenches and concrete infilled trenches, and the applications of geosynthetics and vibro-compaction, buried concrete column and ballasted column, which are further developed from ground improvement methods. All of these methods have been evaluated in two cases: a control case (normal weather pattern) and the adverse climate case (extreme climate conditions).

This study reveals that the resonator-based meta-structures are not a viable solution to mitigate ground-borne vibration and noise because their life-cycle costs are significantly high compared with the other methods. Geogrids are the cheapest method but their performance is relatively insignificant compared with the other methods, which is why it is better used to complement other ground improvement methods. Such combinations could significantly reduce the whole life cost compared with the ground improvement method alone. This study is the world's first to highlight the sustainability of ground-borne vibration mitigation by identifying the impact of the extreme climates on the whole life cost. It was found that the lifecycle costs of all methods tend to increase in an adverse climate due to the increase in the maintenance cost. In addition, the parametric studies have demonstrated that some mitigation methods are more sensitive than another. The most sensitive method is the Geofoam infilled trenches due to the vulnerability and performance reduction of the Geofoam under flooding conditions. This study has clearly shown that to enhance sustainability and lifecycle improvement, the impact of the climate should be taken into account over the whole life cycle. Future work includes the lifecycle evaluation of carbon emissions, considering the extreme climate conditions.

Author Contributions: S.K. and V.M. developed the concept of study. V.M. carried out critical design and analysis. S.K. validated the results. S.K. and V.M. wrote the manuscript.

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Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

Appendix A

Table A1. The illustrations and design performance of the ground-borne noise and vibration solutions.

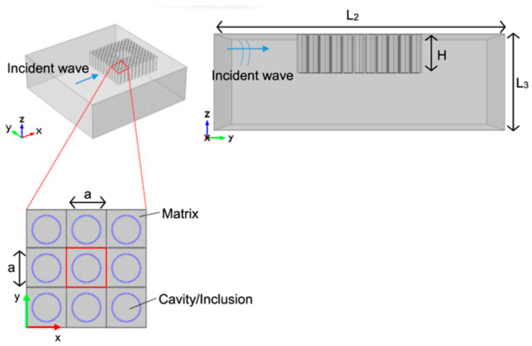
Method	Illustration	Noise and Vibration Reduction as Design
Resonator #1 [18]		No experimental data but a high level of suppression expected

Table A1. *Cont.*

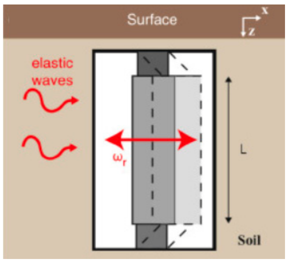
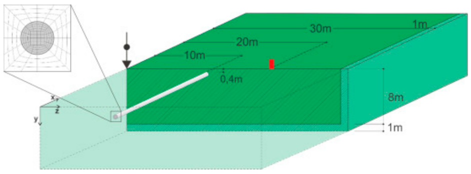
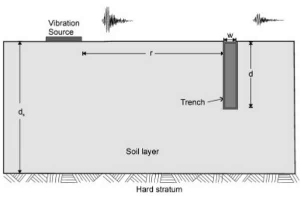
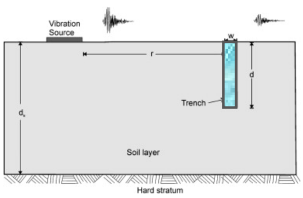
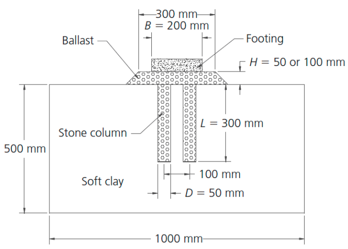
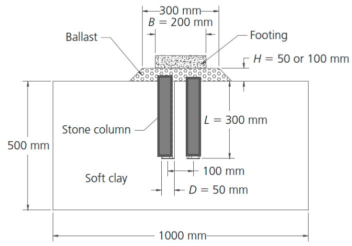
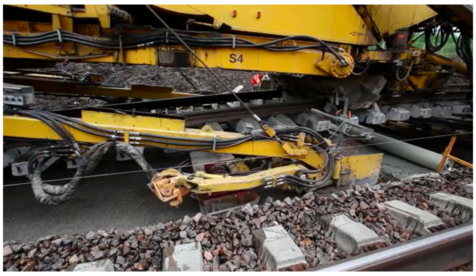
Method	Illustration	Noise and Vibration Reduction as Design
Resonator #2 [19]		5 to 60 dB (longitudinal)
Inclusion [20]		0 to 12 dB (3D effects)
Geogrid [22,23,40]		0–10 dB (depending on the layer stiffness)
Composite sleepers [24,41–43]		1–8 dB (depends on the manufacturing processes)
Concrete filled trench [25,26,44]		0 to 6 dB (depending on the material properties)
Geofoam filled trench [25,26]		0–12 dB (depending on the material properties)
Ballast column [29,30]		0–3 dB

Table A1. *Cont.*

Method	Illustration	Noise and Vibration Reduction as Design
Buried concrete column [31,45]		0–3 dB
Vibro-compaction [31]		0–10 dB (depending on the layer stiffness)

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